Table 5. Community and assemblage structure: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Taxonomic Group or Specific Attributes	Representative References		
Taxa Richness ¹	Scleractinian corals	Aronson et al., 1994 English et al., 1994		
	Chaetodonts	Reese, 1981 & 1994 Crosby and Reese, 1996 Ohman et al., 1998		
	Larval fish assemblages	Doherty, 1991		
	Sessile reef assemblage	Alcolado et al., 1994		
	Coelobites	Choi, 1982		
	Stomatopod crustaceans	Erdmann and Caldwell, 1997 Steger and Caldwell, 1993		
	Amphipods	Thomas, 1993		
	Soft-bottom benthic assemblage structure	Bilyard, 1987 Gray and Mirza, 1979		
Relative Abundance ²	Commercial fish/invertebrate species	Reef Check, 2000		
and Dominance ³	Macrophytic algal blooms	McManus et al., 1997		
	Heterotrophic macroinvertebrates	Dustan and Halas, 1987 Risk et al., 1994		
	Internal bioeroders	Risk et al., 1995 Holmes, 1997 Holmes et al., 2000		
	Corallivores	Birkeland and Lucas, 1990		
	Foraminifera	Hallock, 1996 Cockey et al., 1996 Hallock, 2000		
	Soft-bottom benthic assemblage structure	Pearson and Rosenberg, 1978		

	Coral morphology triangles	Edinger and Risk, 1999
Size Frequency Distribution ⁴	Coral population colony size structure	Bak and Meesters, 1998
	Stomatopod population size frequency	
		Erdmann and Sisovann, 1999

¹ Taxa richness is measured as number of distinct taxa and represents the diversity within a sample. Taxa richness usually consists of species level identifications but can also be evaluated as designated groupings of taxa, often as higher taxonomic groups (i.e., genera, families, orders, etc.) in assessment of invertebrate assemblages.

² Relative abundance of taxa refers to the number of individuals of one taxon as compared to that of the whole assemblage. The proportional representation of taxa is a surrogate measure for assemblage balance that can relate to both enrichment and contaminant problems.

³ Dominance, measured as percent composition of dominant taxon or dominants-in-common, is an indicator of assemblage balance or lack thereof. It is an important indicator when the most sensitive taxa are eliminated from the assemblages and/or the food source is altered, thus allowing the more tolerant taxa to become dominant.

⁴ Size frequency distributions describe the percentage of individuals in a population or assemblage that fall within defined size categories. Skew of these distributions from known baseline distributions can be a sensitive indicator (e.g., indicate occurrence of past pulse disturbance that eliminated all adults, etc.)

Table 6. Taxonomic Composition: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Taxonomic Group or Specific Attributes	Representative References		
Identity ¹	Reef Check key taxa of regional ecological importance	Hodgson, 1999		
Sensitivity ²	Larval fish assemblages	Doherty, 1991		
(intolerance)	Amphipods	Thomas, 1993		
	Foraminifera	Hirschfield et al., 1968 Hallock, 1996 Cockey et al., 1996 Hallock, 2000		
	Stomatopod crustaceans	Erdmann and Caldwell, 1997		
Rare or Endangered Key Taxa ³	Commercially valuable fish/invertebrate species	Reef Check, 2000 McManus et al., 1997		

¹ Identity is knowledge of individual taxa and associated ecological patterns and environmental requirements. Key taxa (i.e., those that are of special interest or ecologically important) provide information that is important to the condition of the target assemblage. The presence of alien or nuisance species may be an important aspect of biotic interactions that relates to both identity and sensitivity.

² Sensitivity refers to numbers of pollutant-tolerant and -intolerant species in the sample.

³ Recognition of those taxa considered to be threatened or endangered provides additional legal support for remediation activities or recommendations.

Table 7. Individual Condition¹: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes Attributes		Representative References		
Disease	Coral vitality/mortality indices	Dustan, 1994 Gomez et al., 1994 Ginsburg et al., 1996		
	Zooxanthellae loss in corals	Jones, 1997		
	Coral diseases	Richardson, 1996 Santavy and Peters, 1997 Rosenberg & Loya, 1999		
Anomalies	Physical damage to corals	Dixon et al., 1993 Chadwick-Furman, 1996 Hawkins & Roberts, 1997 Jameson et al., 1999		
	Ectoparasites on reef fishes	Evans et al., 1995		
	Developmental defects in reef fishes	Lisa Kerr, University of Maryland, Baltimore, USA, pers. comm.		
	Gastropod imposex	Ellis and Pattisina, 1990 Gibbs and Bryan, 1994		
	Coral fertilization rate	Harrison and Ward, in review		
	Expression of stress-induced genes in corals	Snell, in progress		
	Molecular biomarkers in corals	Downs et al., in press		
Contaminant Levels	Depth charge chemicals in damselfish	Jameson, 1975		
	Amphipod burrowing behavior	Oakden et al., 1984		
	Bioaccumulation of metals, phosphorus in coral skeletons	Dodge et al., 1984 Hanna and Muir, 1990		
	Metal bioaccumulation in macrophytes	Brown and Holly, 1982		

	Bioaccumulation in molluscs	Goldberg et al., 1978	
	Bioaccumulation in sponges	D. L. Santavy, U.S. EPA Office of Research and Development, Gulf Ecology Division, pers. comm.	
	Nitrogen isotope ratios in coral skeletons, stomatopod tissues	Risk et al., 1994 Heikoop et al., 2000 Risk and Erdmann, 2000	
Metabolic/Growth Rate	Coral growth rate	Brown, 1988 Edinger et al., 2000	
	Chaetodont territory size, antagonistic encounter rate	Hourigan et al., 1988 Crosby and Reese, 1996	
	Giant clam shell growth rate	Ambariyanto and Hoegh-Guldberg, 1997 Belda et al., 1993a	
Reproductive Condition/ Fecundity	Coral fecundity and fertilization rates	Richmond, 1994; 1996 Ward and Harrison, in press Harrison and Ward, in review	

¹ Individual condition metrics generally focus on chronic exposure to chemical contamination. The condition of individuals can be rated by observation of either physical (morphological), chemical, or behavioral characteristics. For example, physical characteristics of individuals that may be useful for assessing chemical contaminants include those that result from microbial or viral infection and teratogenic or carcinogenic effects during development of that individual. Metrics of this nature have been implemented successfully in freshwater fish multimetric indexes (e.g., % diseased individuals). The underlying concept of the individual condition approach in biomonitoring is that contaminant effects occur at the lower levels of biological organization (i.e., at the genetic, cell, and tissue level within individual organisms) before more severe disturbances are manifested at the population or ecosystem level. Individual condition metrics may provide a valuable complement to ecological metrics if they are of pollutant-specific nature, responsive to sublethal effects, and the time and financial costs for the measurement are consistent with available resources.

Table 8. Biological Processes: An analysis of existing research in relation to the types of attributes that should be incorporated into coral reef indexes of biotic integrity.

Types of Attributes	Attributes	Representative References		
Trophic Dynamics	Benthic shift to heterotrophic macroinvertebrates	Birkeland, 1987 Hallock, 1988 Risk et al., 1994 Tomascik et al., 1994		
	Foraminifera shift to taxa lacking algal symbionts	Cockey et al., 1996 Hirschfield et al., 1968 Hallock, 2000		
Productivity/ Bioaccretion Rates	Whole reef productivity/ calcification profiles	Barnes, 1983 Chalker et al. 1985		
Predation/Grazing	Human predation on reef fish	Smith-Vaniz et al., 1995		
Rate	Changes in sea urchin predation rates	McClanahan, 1988 McClanahan and Muthiga 1989 McClanahan and Mutere, 1994		
Settlement/Recruit ment Rate	Coral recruitment	Tomasick, 1991 Hunte and Wittenberg, 1992 Richmond, 1994; 1996 Ward and Harrison, 1997		
	Crustacean recruitment (stomatopods, lobster)	Herrnkind et al., 1988 Erdmann and Caldwell, 1997 Steger and Caldwell, 1993 ENCORE team, in review		
	Gastropod recruitment	Garrity and Levings, 1990		

A Research Strategy For Creating Coral Reef IBIs

The following research strategy should help focus policy makers and the scientific community on filling the research and information gaps necessary to develop multimetric indexes for coral reef assessment.

The approach of using IBIs and biological criteria for coral reef assessment is unique and different from previous coral reef monitoring and assessment efforts in the following ways.

- Coral reefs are classified so comparisons between similar environments can be made. If metrics are correctly calibrated and scored, it is also possible to compare across classes of reefs (i.e., the resultant IBI is directly comparable despite coming from different types of reefs).
- Minimally disturbed sites are used as reference sites from which to compare monitoring sites.
- Only metrics are used that show a quantitative dose-response change in attribute value that is documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation.
- IBIs are designed to provide a unique early warning characteristic.

Well constructed multimetric indexes typically examine two or more assemblages because different organism groups react differently to perturbation (Table 9). The more diverse the measures used, the more robust the investigative techniques and the more confidence the manager can place in the results. However, this idea must be reconciled with the limitations of the costs of multiple and diverse surveys and the relative availability of reliable scientific methods to measure some assemblages. The most promising approaches will likely be measures of sessile epibenthos, benthic macroinvertebrates, fish, macrophytes, phytoplankton, and zooplankton (Gibson et al., 1997).

Table 9. Types of metrics, suggested number of metrics of each type, and corresponding levels in the biological hierarchy. Well-constructed multimetric indexes contain the suggested number of metrics from each type and therefore reflect multiple dimensions of biological systems (Karr and Chu, 1999).

Metric type	Number	Individual	Population	Community	Ecosystem	Landscape
Taxa richness	3-5	X	X	X	X	
Tolerance-intolerance	2-3		X	X		
Trophic structure	2-4			X	X	X
Individual health	1-2	X				
Other ecological attributes	2-3	X	X	X	X	X X

The actual sampling regimes that will be used to measure the attributes listed in the research strategies are critical and require development. One of the biggest challenges will undoubtedly come from trying to get diverse people to agree on a standard sampling regime. The tendency to argue for favorites should be replaced by a systematic effort to define the kind and amount of sampling that is necessary to reliably detect differences among sites. For each IBI, one needs to devise the techniques used to sample the various organisms and to define which organisms are most important to sample (i.e., which organisms give sampling efficiency and a robustness to the results that gives confidence in the resulting inferences). Because results will be compared in time and space it is crucial that standard methods be developed and tested. Another crucial step will be the use of an analytical framework that gives clear results, and that extracts the most relevant and important insights from the data collected. Oftentimes that requires all of us to think outside the boxes that we are used to thinking in.

Key components of sampling design and analysis include sampling across the full range of biological condition from minimally influenced by human action to severely degraded. Care should be taken to avoid mixing different environment types. Sampling and analysis should focus on finding differences across that range of places without getting bogged down in the other sources of variation that are real but irrelevant (e.g., seasonal changes don't have to all be documented and understood; one does not have to have sampled every microhabitat within the system; one does not have to know how every sampling gear and protocol works; all resident species do not have to be recorded). At the same time, one has to work carefully to define the number of samples necessary to make robust inferences about the condition of places (to be sure that we don't have an excess of data or too few data). In our experience, biologists claim to need far more data than they actually need and then they tend not to look at the things that are most relevant to find patterns that are clearly related to the gradient of human influence/biological condition.

The mixing of sampling methods (e.g., transects and quadrats) is another challenge, in places like coral reefs, that are hard to sample with a standard single method. Early work on stream invertebrates hoped to capture all taxa in all microhabitats but the creation of such composite samples often created difficulties in data interpretation (Parsons and Norris 1996) while samples from single habitats were adequate to access the condition of sites (Kerans et al., 1992). The best approach for coral reef ecosystems can only be defined by systematic study and evaluation of the level of sampling necessary to provide high quality and easily interpreted data.

All sampling methods need to have precise sample effort rules (even if a multiple sampling approach is required, each should be based on a standardized sample effort). When that is done, it is possible to evaluate the best possible way to express biological results (e.g., absolute abundance, relative abundance, taxa richness) as well as to define the best components of biology to be used (e.g., predator taxa richness, omnivore relative abundance, etc.).

Our recommendation is to limit the number of sampling methods (even though we know much information is not being captured) to foster development of standard methods and to limit the time and costs of sampling efforts to the minimum necessary to provide reliable and easily interpreted results. Neither all microenvironments nor all taxa prsent need to be included in standard sample efforts. Furthermore, for sampling programs to be used by diverse agencies and organizations, sampling costs must be controlled. The more efficient and cost effective the sampling at a site the more groups can afford to participate and the more sites that can be sampled. An example of this type of approach would be a benthic cryptofauna IBI whereby a robust quadrat sampling technique would be used to sample all the rubble dwellers in 1 meter square quadrats placed upon reef flats (relatively much easier to sample microhabitats that are usually quite homogenous and whereby the ethical issues of destroying live coral are avoided). This type of sampling technique would allow sampling of the majority of the most promising indicator taxa, including stomatopods, amphipods, forams, boring sponges, boring bivalves, crabs, upogobeiid shrimps and other crustaceans, select species of echinoderms, many polychaetes and platyhelminths, etc. This would be an objective sampling technique, low tech, easily done even snorkeling (without scuba), and would generate data that reflects both species composition and abundances of the organisms present in the sampled environment.

In the research strategies, we focus primarily on relative abundance and taxa richness rather than absolute abundance metrics. Past experience in fresh and marine waters showed that relative abundance metrics worked best because of the often large shifts in absolute abundances in species and their often patchy distributions (also single species have not been found to be very good indicators in fresh water situations) (J. R. Karr, personal observation). In the research strategies we include a few abundance attributes (in the spirit of keeping an open but cautious mind) in the endangered species category, but predict that the taxa richness and relative abundance measures will most likely yield the strongest signals. One problem with an endangered species (as a single species) focus is that their ranges are often limited and thus the signal from that may not be very widely applicable.

Tables 10-15 outline research priorities for creating coral reef IBIs. These tables use the framework in Figure 1 to define the types of attributes, build upon existing coral reef research and draw from the successes of other freshwater and marine IBIs (Karr and Chu 1999, Gibson et al., 1997, Davis and Simon 1995, Simon, 1996). Other attributes that have not been explored are also included in the tables as potential research subjects. These tables are provided as a starting point and are not intended to preclude ideas for other new metrics that may be appropriate for coral reef IBIs.

In freshwater environments:

Total taxa richness (total number of taxa present in a sample),

- Richness of particular taxa or ecological groups,
- Taxa richness of intolerant organisms,
- Relative abundance of stress tolerant taxa (% of all sampled individuals),
- Trophic organization, e.g., relative abundance of predators or omnivores, and
- Relative abundance of individuals with deformaties, disease, lesions or tumors

have been consistently reliable (i.e., show change over a gradient of human-induced degradation) regardless of taxon used or habitat sampled (Karr and Chu 1999) and are used as a starting point for Tables 10-15.

The Importance of Understanding Tolerant and Intolerant Coral Reef Taxa

Indicator taxa are those organisms whose presence (or absence) at a site indicates specific environmental conditions. If an organism known to be intolerant of pollution is found to be abundant at a site, high water quality conditions can be inferred. On the other hand, dominance by pollution tolerant organisms implies a degraded condition. When available, indicator taxa are an important, cost-effective preliminary survey tool for site assessments.

A comprehensive review of coral reef intolerant taxa was conducted by Jameson et al. (1998). Thomas (1993) reviews the use of amphipods and Erdmann and Caldwell (1997) review the use of stomatopods in coral reef monitoring situations. Hallock (2000) outlines the intolerant features of foraminifera and will develop a compact disc on the FORAM protocol for use in low tech settings. In temperate marine waters, Swartz et al. (1985; 1986; 1994) demonstrated the sensitivity of the amphipod *Rhepoxynius abronius* to the complex contaminant mixture along pollution gradients from the Los Angeles County Sanitation Districts' sewage outfalls. Other studies performed by Swartz et al. (1994) at a designated Superfund site in San Francisco Bay showed that acute sediment toxicity lab tests of *R. abronius* reliably predicted biologically adverse sediment contamination in the field.

A well-known indicator for degraded systems is the polychaete *Capitella capitata*. *C. capitata* and its related species are collectively known as the C. *capitata* complex. In general, the presence of this tolerant taxon corresponds to a dominance of deposit feeders that colonize an area as organic pollution increases. Swartz et al. (1985) observed dominance of *Capitella* near sewage outfalls. A recent study in the MidAtlantic Bight by the U.S. Army Corps of Engineers (1996) suggests that the polychaete *Amastigos caperatus* may have indicator potential similar to the *Capitella* complex.

The challenge in using pollution tolerant indicator organisms is that some of these organisms may be ubiquitous and found in naturally occurring organically enriched habitats as well as in minimally disturbed waters. To be useful as an indicator, they must have displaced other, less robust taxa and have achieved numeric dominance. An example of this dilemma is the use of the protozoan genus *Acanthamoeba* as a sewage indicator. Because the animal is capable of encysting, it is present as a public health indicator in sediments long after less durable indicator groups such as the coliform and pseudomonas groups have perished. This same longevity, however, argues against use of the organism as an indicator in open waters because it can be found distributed in sediments far away from the original source of sewage pollution and long after the plume has dispersed (Gibson et al., 1997).

The best option may be the paired use of both pollution tolerant and intolerant indicator organisms. If both indicators change concurrently in opposite directions, more confidence can be placed in the interpretation. When indicator species are employed in tandem for impact investigations, a gradient of species distribution can often be identified. Such a gradient might progress from the most degraded waters, having low diversity communities dominated by pollution tolerant opportunistic species, to undisturbed or minimally disturbed waters having diverse communities comprised of a wide range of taxa, including pollution sensitive ones and some that are pollution tolerant.

Much work needs to be done to understand the tolerance and intolerance of coral reef invertebrates, fishes and plants to specific human activities and mixes of human activities. Once obtained, this understanding will provide useful diagnostic tools to coral reef managers and result in the acquisition of management information and not just the collection of monitoring data.